

# On the Origin of the Lightest Molybdenum Isotopes

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## ABSTRACT

We discuss implications of recent precision measurements for the  $^{93}\text{Rh}$  proton separation energy for the production of the lightest molybdenum isotopes in proton-rich type II supernova ejecta. It has recently been shown that a novel neutrino-induced process makes these ejecta a promising site for the production of the light molybdenum isotopes and other “p-nuclei” with atomic mass near 100. The origin of these isotopes has long been uncertain. A distinguishing feature of nucleosynthesis in neutrino-irradiated outflows is that the relative production of  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$  is set by a competition governed by the proton separation energy of  $^{93}\text{Rh}$ . We use detailed nuclear network calculations and the recent experimental results for this proton separation energy to place constraints on the outflow characteristics that produce the lightest molybdenum isotopes in their solar proportions. It is found that for the conditions calculated in recent two-dimensional supernova simulations, and also for a large range of outflow characteristics around these conditions, the solar ratio of  $^{92}\text{Mo}$  to  $^{94}\text{Mo}$  cannot be achieved. This suggests that either proton-rich winds from type II supernova do not exclusively produce both isotopes, or that these winds are qualitatively different than calculated in today’s supernova models.

*Subject headings:* supernovae, nuclear reactions, nucleosynthesis

Burbidge et al. (1957) described the synthesis of elements heavier than the iron group in terms of three main processes: slow (*s*-process) neutron capture, rapid (*r*-process) neutron capture, and proton capture (the *p*-process). It was believed that proton capture could account for the nuclei blocked from synthesis in neutron processes by stable isotopes that prevent their production through  $\beta$ -decay. Subsequent studies of nucleosynthesis in stellar environments found the densities and temperatures needed for the *p*-process difficult to obtain. Today the origin of the *p*-nuclei between  $A = 92$ –126, and in particular  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$ , is one of the great outstanding mysteries in nuclear astrophysics.

A number of potentially promising production sites and alternative nucleosynthesis paths for producing the  $p$ -nuclei have been proposed. These include neutron-rich outflows from nascent neutron stars (Hoffman et al. 1996), outflows from black hole accretion disks (Surman et al. 2006), and incredibly neutrino-irradiated neutron-rich outflows from neutron stars (Fuller & Meyer 1995). Recently it has been shown that a novel nucleosynthesis process occurring in proton-rich supernova ejecta could efficiently synthesize  $p$ -nuclei between strontium and palladium (Fröhlich et al. 2006; Pruet et al. 2006). In this process neutrino capture on free protons produces a small reserve of free neutrons. These neutrons induce (n,p) reactions that push the nuclear flow beyond the waiting point nuclei with long weak decay half-lives (starting with  $^{64}\text{Ge}$ ). A feature of the neutrino-accelerated synthesis is that all of the light  $p$ -process nuclei are made through decay of radioactive proton-rich progenitors.

In this Letter we develop quantitative arguments to test and place limits on neutrino-irradiated supernova outflows as the site responsible for producing the two lightest molybdenum isotopes. The observed ratio of these isotopes in the sun provides a key diagnostic. We will show that this ratio in supernova outflows is exquisitely sensitive to the proton separation energy for  $^{93}\text{Rh}$ . As a result the production of the two lightest molybdenum isotope in proton-rich winds with a relative abundance equal to that observed in the sun is only possible for a narrow range of proton separation energies near  $S_p = 1.65$  MeV. This value was consistent with the previous empirically-based estimate  $S_p = 2.0 \pm 0.5$  MeV Audi et al. (2003). However, recent precision measurements by Fallis et al. (2008) and Weber et al. (2008) find that  $S_p = 2.00 \pm 0.01$  MeV. Because these measurements do not give agreement with the diagnostic afforded by the solar ratio, there is an indication that proton-rich supernova outflows are not exclusively responsible for producing both light molybdenum isotopes.

To set the stage for a quantitative discussion we show in Figure 1 the net nuclear flows governing synthesis of the lightest molybdenum isotopes in a supernova outflow. This outflow is taken from the 2D supernova simulations of Janka et al. (2003) and corresponds to "trajectory 6" in the nucleosynthesis study of Pruet et al. (2006). This is one of only two outflow trajectories calculated by Janka et al. (2003) that efficiently synthesized  $A > 90$   $p$ -nuclei. We will take this outflow trajectory, which is characterized by an entropy per baryon  $s/k_B = 77$  and electron fraction  $Y_e = 0.57$ , as our baseline. Figure 2 shows conditions during the first three seconds post core bounce in trajectory 6.

At temperatures larger than about 1 billion degrees, nuclear flows governing synthesis of the light molybdenum isotopes are regulated by a competition between ( $p, \gamma$ ) and the inverse ( $\gamma, p$ ) reactions. This balance is set chiefly by proton separation energies. From Figure 1 it can be seen that the proton separation energies for Rh isotopes with mass numbers between

89 and 91 are small. As a result, the even-even nucleus  $^{92}\text{Pd}$  is not appreciably populated and does not serve as a progenitor for  $^{92}\text{Mo}$ . Instead the main flow path detours along  $Z=44$  (Ru) until reaching the  $N=48$  isotonic line. It is these  $N=48$  nuclei that serve as progenitors for the light molybdenum isotopes.

Figure 3 depicts the late time evolution of the mass fractions ( $X$ ) for the  $A = 92$  and  $94$  isobars that contribute to  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$ . Approximately 90% of the final  $^{92}\text{Mo}$  abundance results from  $\beta^+$  decays starting at  $^{92}\text{Ru}$ . A larger fraction of the final  $^{94}\text{Mo}$  inventory is attributed to decays starting with  $^{94}\text{Pd}$ .

Since  $N = 48$  isotones are the main progenitors for the two light molybdenum isotopes, the final abundance of  $^{92}\text{Mo}$  relative to  $^{94}\text{Mo}$  is set principally by nuclear flow out of  $^{92}\text{Ru}$ . Proton capture on this nucleus produces  $^{93}\text{Rh}$ , which in turn leads to efficient synthesis of the tightly bound and even-even  $^{94}\text{Pd}$ . Though an important part of the nucleosynthesis occurs after rates have become too slow to maintain nuclear statistical equilibrium, we can gain some qualitative insights into the importance of the proton separation energies by considering the case where the outflowing ejecta is still hot. Under this condition  $^{92}\text{Ru}$  and its proton capture daughter  $^{93}\text{Rh}$  are in equilibrium with each other. The relative abundance of the two nuclei is given by

$$\frac{Y_{93}}{Y_{92}} = 5.15 \cdot 10^{-11} \left( \frac{G_{93}}{G_{92}} \right) \left( \frac{\rho Y_p}{T_9^{3/2}} \right) \exp(S_p(93)/T_9), \quad (1)$$

where  $Y$  represents the number fraction ( $Y_i = \rho N_A n_i$ ),  $G$  represents the nuclear partition function,  $S_p(93)$  is the proton separation energy for  $^{93}\text{Rh}$  and  $\rho$  is the density in  $\text{g}/\text{cm}^3$ . Because the proton separation energy for  $^{93}\text{Rh}$  is relatively small compared to that for  $^{94}\text{Pd}$ , it plays the key role in setting the final abundance of  $^{92}\text{Mo}$  relative to  $^{94}\text{Mo}$ . Qualitatively, eq. 1 says that an increase in the  $^{93}\text{Rh}$  proton separation energy tends to decrease the  $^{92}\text{Mo}/^{94}\text{Mo}$  ratio.

Quantitative results for the molybdenum production can be gained from detailed nuclear network calculations. Our goal is to see whether the solar ratio Lodders (2003)

$$\frac{X(^{92}\text{Mo})}{X(^{94}\text{Mo})} = 1.57 \quad (2)$$

can be synthesized in proton-rich supernova ejecta. Using the recently measured  $^{93}\text{Rh}$  proton separation energy, the outflow characteristics from the simulation of Janka et al. (2003), and the estimates of nuclear reaction rates described in Pruet et al. (2006) gives a ratio of the two lightest molybdenum isotopes of  $X(^{92}\text{Mo})/X(^{94}\text{Mo}) = 0.35$ . This is about a factor of five too small compared to the solar ratio in eq. 2.

If today's supernova models were perfect then we could infer directly from the dis-

crepancy between the calculated and solar values that proton-rich supernova winds are not exclusively responsible for making both light molybdenum isotopes. However, there are potentially important uncertainties in our understanding of neutron star winds. From the perspective of trying to calculate nucleosynthesis there are a few key aspects of the outflow. These include the entropy of the wind, the electron mole number,  $Y_e$ , and the dynamic timescale characterizing the evolution of the wind (Qian & Woosley 1996).

To see if uncertainties in calculations of the outflow could account for the discrepancy between the calculated and observed molybdenum ratio, we calculated the nucleosynthesis for a great variety of assumptions about conditions in the supernova. Results of modifying the electron fraction and entropy are shown in Figure 4. Entropy was varied by simply uniformly re-scaling the density as a function of time, which is approximately correct because of the relation  $s/k_b \propto T^3/\rho$  valid in the regime important for nucleosynthesis (Qian & Woosley 1996). With the recently measured value for the proton separation energy the solar ratio can only be achieved for  $Y_e \approx 0.52$ . However, as Figure 5 shows, at this electron fraction the overall production of molybdenum plummets unless the entropy is larger than about 120. This is much higher than the value of 77 found in the supernova calculations. For smaller entropies the production factor for  $^{92}\text{Mo}$ , which provides a measure of the total amount of the isotope produced, is

$$P(^{92}\text{Mo}) = \left( \frac{X(^{92}\text{Mo})}{X_{\odot}(^{92}\text{Mo})} \right) \left( \frac{M_{\text{wind}}}{M_{\text{ejecta}}} \right) < 0.07, \quad (3)$$

where  $M_{\text{wind}} \approx 1.04 \cdot 10^{-3} M_{\odot}$  is the total mass of material producing  $^{92}\text{Mo}$  in the calculations of Janka et al. (2003) and  $M_{\text{ejecta}} \approx 13.5 M_{\odot}$  is the total mass of material ejected by the supernova. To account for the solar abundance of isotopes attributed to type II supernovae, the production factor has to be approximately 10 (Timmes, Woosley & Weaver 1995). This is found by calculating the production factor characterizing isotopes such as  $^{16}\text{O}$  that are believed to be chiefly produced in supernovae (Woosley & Weaver 1995). The needed production factor is also arrived at through detailed galactic chemical evolution studies that describe stellar mass recycling and galactic inflow and outflow (Mathews et al. 1992; Timmes, Woosley & Weaver 1995). A production factor near 10 implies that if winds with  $Y_e \approx 0.52$  were responsible for the two light molybdenum isotopes then the total mass of material producing these isotopes would have to be more than an order of magnitude larger than that calculated in current supernova models.

We also investigated the influence of uncertainties in the dynamic timescale on the ratio of the light Mo isotopes. At high temperatures the e-folding time for density sets the production of “seed” nuclei with mass greater than  $A=12$  and at low temperatures it sets the net number of neutrino captures on protons. To approximately gauge the influence of

uncertainties in the dynamic timescale we simply scale the time coordinate for our baseline trajectory by +50% (see Figure 2). The ratio of the light Mo isotopes was essentially unchanged. Given this weak sensitivity it seems reasonable to neglect errors associated with dynamic timescale. As well, the study of Qian & Woosley (1996) find that a factor of two change in dynamic timescale corresponds to a factor of two change in neutron star radius or neutrino luminosity.

In the same way that one can determine the outflow characteristics that reproduce the observed molybdenum ratio, we can also determine the  $^{93}\text{Rh}$  proton energy consistent with the observed ratio. For entropies less than 140, and outflows that give a  $^{92}\text{Mo}$  production factor larger than 0.7, we find that the solar ratio can only be recovered if  $S_P(93) = 1.65 \pm 0.1$  MeV. This is ruled out by the recent mass measurements.

It is also possible that uncertainties in other nuclear physics inputs apart from the  $^{93}\text{Rh}$  proton separation energy could explain the discrepancy between the calculated and solar molybdenum ratio. We studied variations consistent with current experimental uncertainties for the  $^{91}\text{Rh}$  proton separation energy and the  $^{92}\text{Rh}$  proton separation energy. Uncertainties in these have effectively no impact on the calculated Mo ratio. We also studied the impact of uncertainties in the charged particle capture cross sections that affect the production of  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$  by increasing the  $^{90}\text{Ru}(p, \gamma)^{91}\text{Rh}$ ,  $^{91}\text{Ru}(p, \gamma)^{92}\text{Rh}$ ,  $^{92}\text{Ru}(p, \gamma)^{93}\text{Rh}$ , and  $^{94}\text{Pd}(p, \gamma)^{95}\text{Ag}$  rates by a factor 100. Because these nuclei nearly are in equilibrium, these variations result in a  $< 1\%$  change in the production factors. Though we can't strictly rule out the possibility, it appears that nuclear physics uncertainties cannot account for the discrepancy in the molybdenum ratio.

In summary, our study of nucleosynthesis using the newly measured value for the  $^{93}\text{Rh}$  proton separation energy suggests the proton-rich supernova ejecta are not exclusively responsible for producing the two lightest molybdenum isotopes unless conditions in these ejecta are quite different than indicated by recent supernova calculations. In particular, the free proton fraction would have to be about three times smaller, and the entropy about fifty units higher. This would have fairly dramatic implications not just for molybdenum production but also for the nucleosynthesis as a whole. It may be interesting to note that the need for a decrease in electron fraction and an increase in entropy also plagues calculations of the  $r$ -process that might occur later in the evolution of the supernova (Qian & Woosley 1996).

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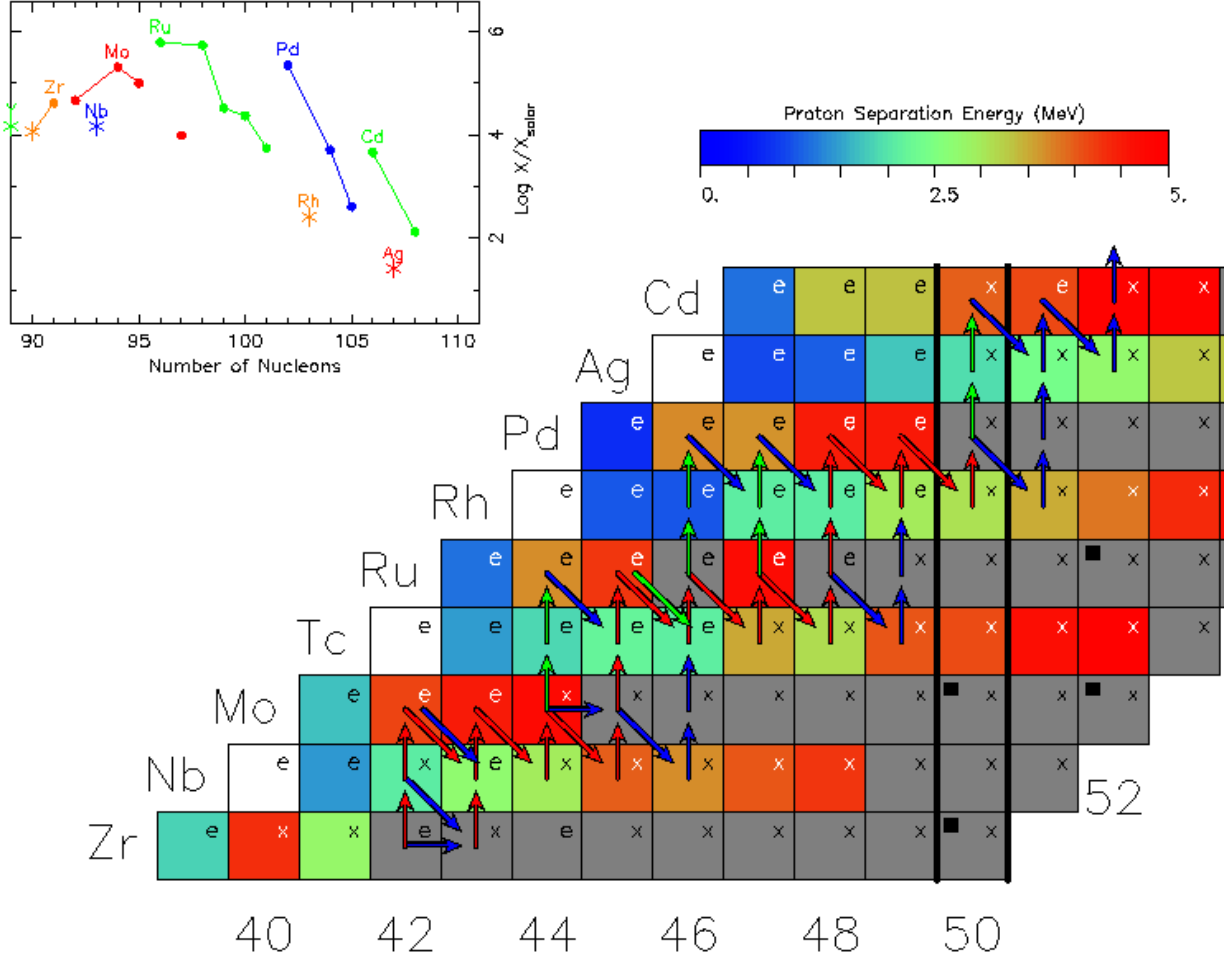


Fig. 1.— Net nuclear flows important in setting the abundance of  $^{92}\text{Mo}$  relative to  $^{94}\text{Mo}$ . At the time shown  $T_9 = 2.06$ ,  $\rho_5 = 2.74$ , and  $Y_e = 0.561$ . Each isotope is color coded to the value of its proton separation energy (red is 5 MeV, blue is 0 MeV, gray and white are above and below this range respectively). An "x" indicates the isotope has an experimentally measured mass excess in the most recent mass evaluation Audi et al. (2003), an "e" represents their extrapolation from measured masses. The arrows indicate the dominant net nuclear flows with color representing strength. All net flows within a factor of 5 of the largest flow in this figure are colored red, those between 5 and 10 are green, and between 10 and 50 are blue. The inset shows the production of the light  $p$ -nuclei relative to the solar abundances. The most abundant isotope in the sun is shown as an asterisk.



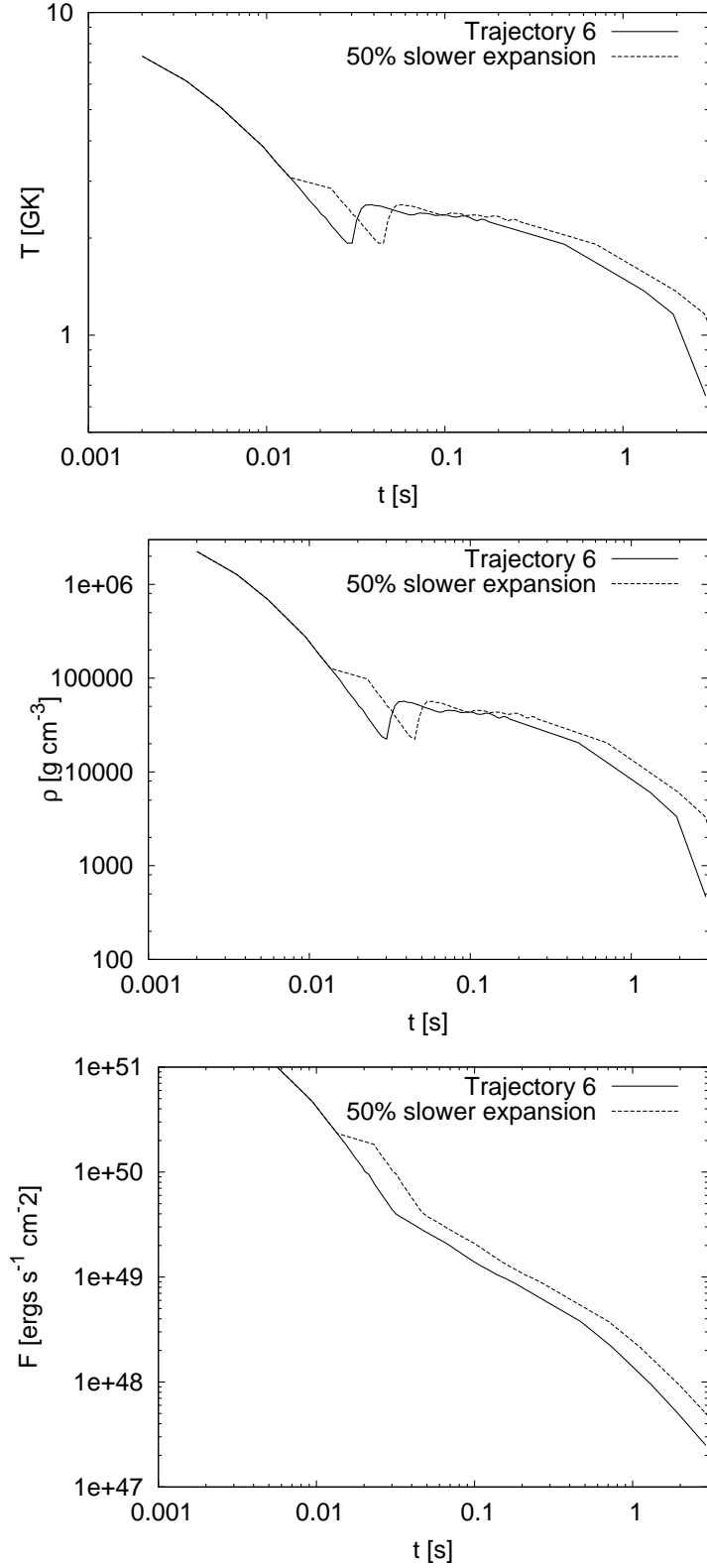


Fig. 2.— Shown are the evolution of the temperature, density, and total neutrino flux for the baseline “trajectory 6” as well as the evolution when the dynamic time scale is changed by 50%.

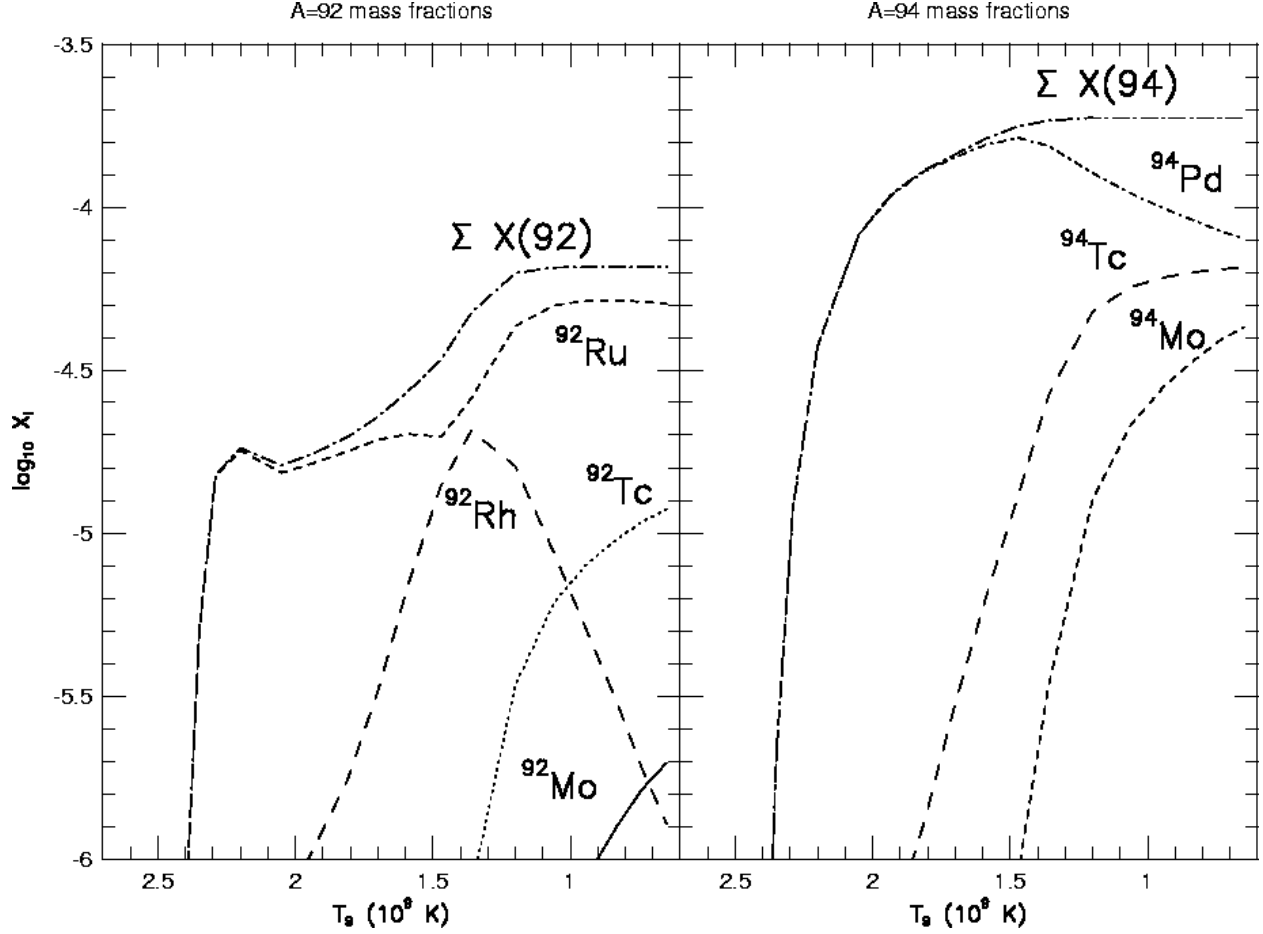


Fig. 3.— Mass fractions of the  $A = 92$  and  $A = 94$  isobars affecting the final abundance of  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$  as a function of freeze out temperature. Note that most of the final yield of these two molybdenum isotopes originates with  $N = 48$  isotones.

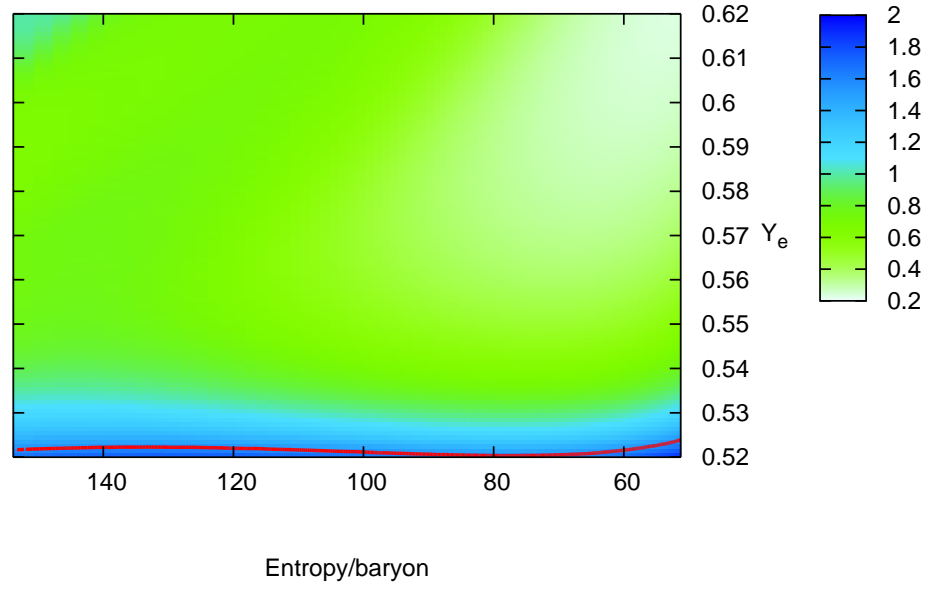


Fig. 4.— The abundance ratio of  $^{92}\text{Mo}$  and  $^{94}\text{Mo}$  as a function of  $Y_e$  and the entropy per baryon. The line very near  $Y_e = 0.52$  shows the solution where  $X(^{92}\text{Mo})/X(^{94}\text{Mo}) = 1.57$ .

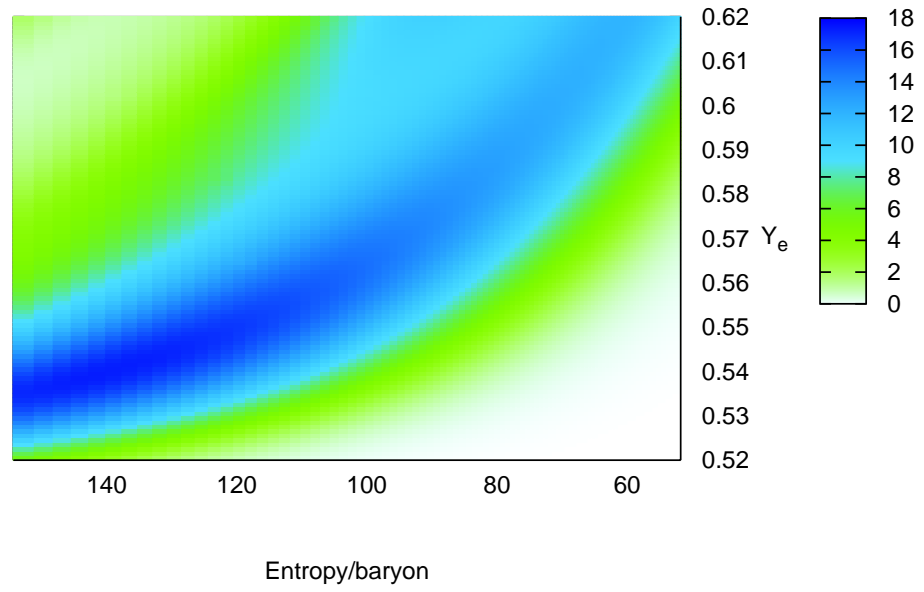


Fig. 5.— The production factor for  $^{92}\text{Mo}$  (eq. 3) as a function of  $Y_e$  and the entropy per baryon.